TITAN'S CLIMATE THROUGH TIME: EFFECTS OF GEOTHERMAL AND TIDAL HEATING.

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Recent studies [1] have shown that Titan's atmosphere may have collapsed in the past due to the photolytic depletion of methane and loss of greenhouse warming. We investigate whether geothermal or other heat sources could prevent this early in Titan's history, and find this is unlikely: Solar evolution and the availability of methane at the surface are the dominant drivers of climate evolution. We find, however, that ocean-atmosphere feedbacks could cause tidal dissipation in a shallow ocean to accelerate and boil off most of the volatile component of an ocean, leading to inhomogeneities of composition among surface liquid reservoirs.

In terms of surface pressure and dominant constituent, Titan's is the most Earth-like atmosphere in the solar system. However, it differs in the much lower insolation it receives (at 9.5 AU, ~15 Wm^{-2}) and in its reducing nature (rather than oxygen, its second principal constituent is methane). Methane photochemistry gives rise to a number of organic gases in the atmosphere, a thick organic haze (with optical depth of order 1-10 in the visible) and hydrogen.

Collapsing Greenhouse

The present surface temperature 94K is elevated by some 22K by a greenhouse effect due to methane, nitrogen and hydrogen, although haze opacity (plus some methane absorption) provide an antigreenhouse of 9K, so the surface is about 12K above the equivalent temperature of 82K [2,3]. Since the hydrogen is produced by methane photolysis, if the methane supply were to have been exhausted (there is as yet no evidence for a significant surface reservoir - the present methane laden atmosphere may be anomalous) the hydrogen and methane warming would disappear. Tropopause temperatures fall, even with the present insolation, to levels where nitrogen can form clouds and rain out. If albedo feedbacks exist, especially for reduced solar luminosity in the early solar system, the atmosphere may have collapsed, with residual pressures of tens or hundreds of millibar and an ocean of liquid nitrogen on the surface.

This collapse process may have been mitigated by other heat sources early in Titan's history, when radiogenic, tidal and accretional heating were stronger. This is especially the case since previous studies [4] have noted that Titan's surface temperature is very sensitive to geothermal heat flow if there is a surface reservoir of volatiles.

Solar Luminosity

The sun's luminosity L may be expressed [5] as $L=L_0[1+0.4(1-t/t_0)]^{-1}$ where L_0 is the present luminosity, and t_0 is the age of the sun (4.6 Gyr). The present insolation (averaged over the surface and time) is ~3.8 Wm^{-2}. In the next 5 Gyr, the sun's luminosity will increase by another 30% or so, and then by an order of magnitude [6]. The effects of this luminosity increase will be profound, but need to be explored in detail with a radiative model.

Radiance from Saturn is about 1/1000th of that from the sun. Evolution models [7] show Saturn's luminosity at about double its present value a few Gyr ago, although the effect of helium rainout is not included. At Saturn's emission temperature of ~100K, most of the flux is in the 100-500 cm^{-1} spectral region, where nitrogen and methane are strong absorbers [2], so this energy is unlikely to reach the surface.

Internal Heat Production

Present-day radiogenic heat production on Titan has been estimated [8] at 4-5x10^{11} W, or ~ 6mWm^{-2}. This is likely to have been higher by a factor of a few early in the solar system, especially since Titan probably received a near-chondritic abundance of K_{40}. Assuming homogenous accretion, Schubert et al. [8] estimated the heat of accretion of Titan at 2.82x10^{29} J. Much of this, however, would have been lost as Titan and its atmosphere formed. The energy of differentiation, released later, amounts to about 12% of the accretional energy. If released evenly over 4.5 Gyr, the latter corresponds to a heat flow of ~ 3 mWm^{-2}.

Recent work by Grasset and Sotin [9] has indicated that a liquid layer (water or water-ammonia) in Titan's interior would persist over geologic time. If this is the case, then the geothermal heat flow has probably been relatively constant (unlike the Earth, where the radiogenic elements are concentrated in the crust, on Titan these are in the core. Thus the heat flow is controlled by the thickness of the upper ice layer only. Grasset and Sotin's calculations show the upper ice layer's thickness - defined by the ice having a viscosity of ten times that of the liquid, or at 140K for 15% water-ammonia - as fairly constant at around 50km. Tidal dissipation [10] in Titan's solid body (principally the outer shell) has been estimated at 5x10^{10} W, based on the present orbital eccentricity e of 0.029. The eccentricity could conceivably have been a factor ~3 higher in the past, and body tide dissipation scales as e^2, so perhaps 5x10^{11} W could be generated, equivalent to the radiogenic heating. The decay time of the eccentricity would be of the order of the age of the solar system.

Thus, surface heating from internal sources adds less than 1% to the insolation, so the evolution of the latter is the dominant driver of the surface energy budget.

A Runaway Tidal Greenhouse

Tidal dissipation in possible surface oceans could be significant. In the case (albeit unrealistic) of a 100m global ocean, dissipation would be ~2.5×10^{12} W, or 30 mWm^{-2} for the present eccentricity. Although this is a small value, 1% of the insolation, it could have interesting effects due to the atmosphere-ocean coupling investigated by McKay et al. [4] . An increase in surface heating by 0.03 Wm^{-2} would lead to a temperature rise of ~2K in the case of a methane-rich (66% relative humidity) ocean. This rise is due to surface warming increasing the amount of nitrogen and methane, the more volatile ocean components, in the atmosphere. The enhanced partial pressures of these greenhouse gases then warm the surface due to increased thermal opacity. McKay et al. showed that this greenhouse warming is stable - the enhanced greenhouse warming is not enough to provide the initial perturbation.

However, this considers only the thermodynamic aspects of the ocean. The evolution of gas into the atmosphere requires a loss of mass from the ocean itself - the 2K temperature rise is associated with a rise in surface pressure of ~100 mbar, or an evaporation of about 15m. Since ocean dissipation scales as the inverse cube of depth, the dissipation would now be 60% higher, requiring an additional temperature rise, and so on. The process would feed back on itself until the ocean 'dried up' - its volatile methane and nitrogen exhausted (note that an ocean composed of ethane does not exhibit this behavior as its vapor pressure is very low at Titan surface temperatures). The ocean dissipation varies as the cube of eccentricity - the temperature rise would be even higher if the eccentricity were larger than the present value.

Thus, while an ocean is thermodynamically stable to perturbations in its temperature state (the enhanced greenhouse is insufficient to prevent gas from being absorbed back in the ocean) a very shallow, methane/nitrogen-rich, global ocean may be unstable with respect to tidal runaway. Tidal effects augment the positive feedback of the thermodynamic equilibrium, such that the state becomes unstable. We note that this unstable state is most probable early in Titan's history, since there is likely to be less involatile ethane present in an ocean, and the eccentricity may have been higher. As the solar luminosity was lower at this point too, formation of a nitrogen ocean by atmospheric rainout is likely if methane became depleted.

However, a global shallow ocean is unlikely due to the presence of topography. Although tidal dissipation is greatly reduced in general if liquids are confined to e.g. crater basins [11], if there are extended features (multi-ring basins, rift valleys, etc.) that could support planetary-scale fluid motion, dissipation could be locally significant and enhanced. In such cases, liquid deposition may be inhibited - as soon as a shallow deposit forms, dissipation boils it off.

The liquid could recondense, however, elsewhere, such as in small crater basins where dissipation is negligible.

This is in contrast to deposition of liquid ethane, which is essentially involatile - while deposits of methane/nitrogen are inhibited in regions of enhanced dissipation (and for that matter, geothermal heat flow and insolation), ethane deposits can form anywhere. There may therefore be lakes/seas of differing composition on Titan, even though all are in thermodynamic equilibrium with the atmosphere.

In conclusion, although some interesting feedbacks exist, after the initial accretion of Titan and the formation of its present nitrogen atmosphere, the only significant drivers of Titan's climate are the availability of methane at the surface, and the solar luminosity. Anomalous impact or geothermal events are likely to have a stronger effect by their delivery of volatiles to the atmosphere than by their thermal effects alone. Tidal dissipation may render shallow volatile liquid deposits unstable.

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